GPS Users Positioning Errors during Disturbed Near-Earth Space Conditions

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ABSTRACT

Operation quality of the Global Navigation Satellite Systems (GNSS) appreciably depends on condition of the near-Earth space environment. Afraimovich et al. (GPS Solutions, 2003, V7, N2, 109) showed, that during geomagnetic disturbances in the near space deterioration of GNSS operation quality is appeared and, as consequence, reduction of positioning accuracy and occurrence of failures in definition of ground based users coordinates are observed. Application of GNSS for the decision of orbital objects navigation tasks allows to increase considerably accuracy of coordinates and parameters of movement definition of such objects. Wickert et al. (J. Communications Technology and Electronics, 2004, V49, N10, 1184) found strong amplitude and phase fluctuations of L-band radio waves on line-of-sight «satellite-to-satellite». However from the viewpoint of GNSS users research of positioning accuracy is of much greater interest. The aim of our research is estimation of GPS ground and orbital users positioning accuracy in different geomagnetic conditions. Interrelation between total electron content (TEC) variations and positioning accuracy during the strong magnetic storms on 29-31 October 2003 we observed on the territory of Northern America. It should be noted that GPS positioning errors increased significantly not only within auroral area but also in the south- west of Northern America, at low enough latitudes (30-35^0 N; 240-255^0 E). High absolute values and steep TEC gradients were observed in this region concurrently. TEC variations intensity in the period range of 1-10 min increases by one order as intensive LS AGW propagates from the northeast to the southwest of the USA. Space-time characteristics of GPS positioning errors are close to the corresponding intensity characteristics of small-scale irregularities. It is in accord with the existing idea that phase slips are caused by GPS radio signals scattering on small-scale irregularities. Latitudinal dependence of GPS-stations positioning accuracy was obtained on a basis of analysis more then 600 GPS-stations which have well known X_0,Y_0,Z_0 coordinates. It was found that absolute errors of coordinate determination are usually greater for GPS-stations at high- and low latitude comparing to these ones at mid latitudes. This dependence is more apparent under magnetic storm condition. The pointed latitudinal dependence is the most noticed for Z coordinate determination errors: this value is grater then X and Y ones and it depends on geomagnetic condition to the greatest extent in all cases we were considered. Low Earth orbiter CHAMP (CHAllenging Minisatellite Payload) with two-frequency GPS – receiver onboard has been chosen for experiment. We used the RINEX (Receiver

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Independent Exchange format) files and the files containing precision coordinates of CHAMP given by the Information system and Data Center at GeoForschungZentrum Potsdam (http://isdc.gfz-potsdam.de/champ). More than 100 passes under undisturbed and about 70 passes under disturbed geomagnetic conditions during January-December 2003 have been processed. We found that both in undisturbed, and in the disturbed geomagnetic conditions, the most probable error of CHAMP positioning is less then 10 m. However in disturbed geomagnetic conditions probability of a significant error occurrence more than 30 m in 1,5 times is higher, then in undisturbed conditions.

1.0 INTRODUCTION

The satellite navigation GPS system has become a powerful factor of scientific and technological progress worldwide. In this connection, much attention is given to continuous perfection of the GPS system and to the widening of the scope of its application for solving the navigation problems themselves, as well as for developing high-precision low Earth orbital and ground-based systems for time and position determinations. Even greater capabilities are expected in the near future through the combined use of the GPS with a similar Russian system GLONASS [1].

The performance of modern global satellite radio navigation systems that utilize the "Earth-Space" radio wave propagation channel is limited by the geospace environment. The main degradation comes from the systematic ionospheric effects of radio wave propagation: the group and phase delay and the frequency Doppler shift. In many instances the degree of manifestation of the above effects has only a weak dependence on the local distribution of electronic density in the ionosphere but is directly correlated with the value of total electron content (TEC) along the radio signal propagation path (Aarons, 1982). In undisturbed geospace conditions the main contribution to the formation of the above-mentioned ionospheric effects is made by the regular TEC component. It undergoes periodic regular variations (seasonal-diurnal, latitudinal, and longitudinal) and can be predicted relatively accurately. A variety of TEC models have been developed to date, which are intended to cancel out the ionospheric influence on the performance of the modern GLONASS and GPS in geomagnetically quiet and weakly disturbed conditions [2], [3].

The situation is more complicated during geomagnetically disturbed conditions of the space environment. The irregular TEC component makes a substantial contribution in this case. The amplitude of random TEC variations with a period from a few minutes to several hours in conditions of geomagnetic disturbances can make up as much as 50% of the background TEC value [4-6]. Furthermore, the amplitude and phase fluctuation range of signals from navigation satellites (NS) at the reception point can exceed the designed level required for the uninterrupted operation of GPS receivers. Under these conditions, the accuracy to which the current location (CL) can be determined is degraded for both low Earth orbital and ground-based users of GPS [7-9]. The study of deep, fast variations in TEC caused by a strong scattering of satellite signals from intense small-scale irregularities of the ionospheric $F2$-layer at equatorial and polar latitudes has a special place among ionospheric investigations based on using satellite (including GPS) signals [10-13].

Recent years extensive studies of mid-latitude phase fluctuations and phase slips of range measurements using GPS in conditions of geomagnetic disturbances were made [14-16], [17-19], [20]. It's known [21-23] that expanse of the auroral oval equatorward the mid-latitude region is accompanied with increasing a number of slips of position determination and decreasing of GPS positioning accuracy. From the point of view of the GPS user significantly greater interest are the investigations into the influence of geomagnetic disturbances on the performance of GPS as a positioning system.

The objective of this paper is to investigate interaction of spatial-temporal characteristics of auroral activity, total electron content (TEC) variations and positioning accuracy during geomagnetic storms of 2000-2003.

Information about the method of processing the data from GPS network was described in earlier works [8], [9]. For low Earth orbital and ground-based GPS user's positioning errors estimating software packages "Navigator" and "Orbital Navigator" developed by authors [7], [9], [23] on a basis of the existing standard RINEX-files processing software TEQC (Translate Edit Quality Check), posted on the Internet at http://tonga.unavco.ucar.edu/software/teqc/Microsoft/2000/Borland/5.0, was used. For determination of auroral oval location data from Space Environmental Monitor were used. The data of 14-17 NOAA POES satellites are available through the Internet at http://sec.noaa.gov/pmap/pmapN.html.

2.0 SPATIAL-TEMPORAL DYNAMICS OF GPS USER'S POSITIONING ERRORS

It is known that deep alterations of geomagnetic field intensity can cause global redistribution of ionosphere plasma. Such redistribution, in its turn, leads to formation of strong steep gradients plasma. It is also known that ionospheric irregularities are generated in areas of enhanced electron concentration gradient. Strong scintillations of amplitude and phase of GPS signals occur due to signals scattering on intensive small-scale ionospheric irregularities with a size of the order of the first Fresnel zone radius (150-300 m). As a result, the signal amplitude may temporarily drop down to below noise level, leading to lost signal lock and failures in range measurements. Then positioning accuracy of GPS as navigation system goes down seriously during strong magnetic storms.

Interrelation between total electron content (TEC) variations, amplitude and phase scintillations of GPS signals and positioning accuracy during the strong magnetic storms on 29-31 October, 2003 we observed on the territory of Northern America. Figure 1 shows the geometry of the experiment on October 29-31, 2003. The hatch-dashed line plots the south boundary of auroral oval at 01:52 UT on October 31, 2003.

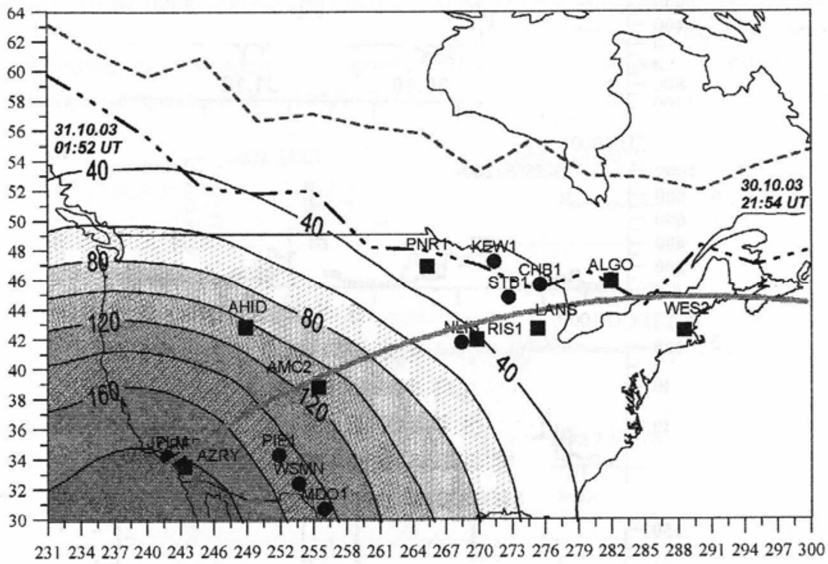

Figure 1: geometry of the experiment on October 29-31, 2003. The hatch-dashed line plots the south boundary of auroral oval at 01:52 UT on October 31, 2003.

Figure 2a presents dependence of H-component of magnetic field intensity at Ottawa station (45.40° N; 284.45° E). Positioning errors $\sigma(t_i)$ at some of GPS stations in the USA area are shown on Figure 2 (d-**e**). One can see significant decreasing of positioning accuracy during the main phase of the magnetic storm for the GPS station KEW1 located at the area of auroral oval southern boundary (Figure 2,d) as well as for the station JPLM, which is in the south-west of the USA.

In the mid-latitude region high gradients of absolute "vertical" TEC value I_0 were noticed. Figure 1 shows the distribution of absolute vertical TEC value I_0, determining using IONEX data from JPLG laboratory for the time 21:00 UT on October 30, 2003. TEC values are assigned by digits in TEC units TECU ($10^{16}m^{-2}$). It is considered that high gradients of TEC cause conditions appropriate for intense small-scale irregularities creation (Coster et al., 2001). In general, it was found that an increase in the level of geomagnetic activity is accompanied by GPS positioning errors increasing; it correlates with the value of the time derivative of H- component of magnetic field intensity (Figure 2).

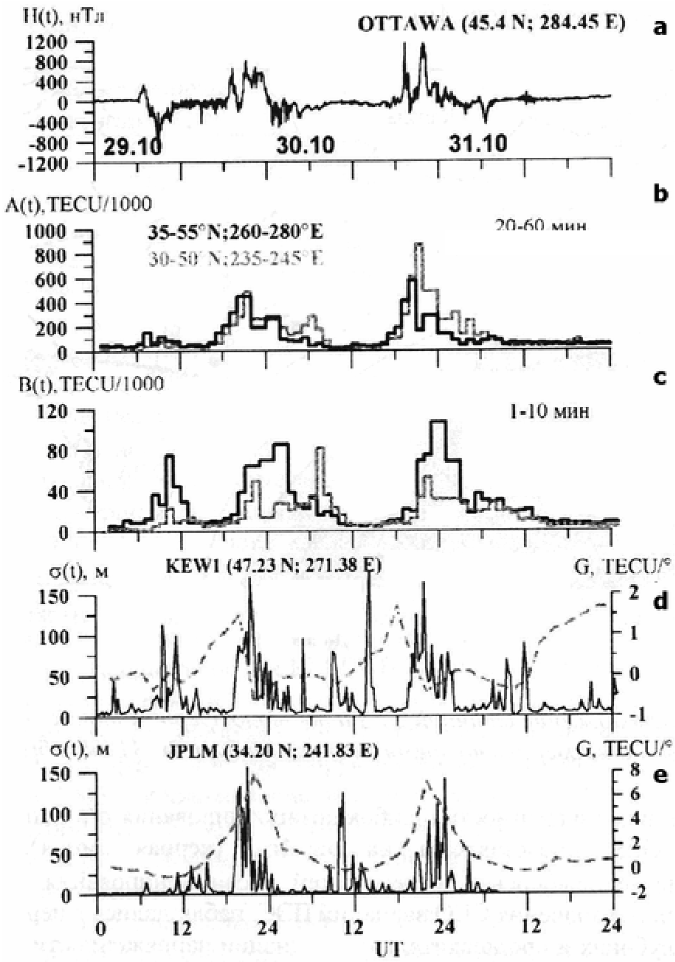

Figure 2: geomagnetic variations (a), TEC standard deviation for GPS-stations in north-east (black line) and south-west (gray line) area of North America (b, c); positioning errors (d, e solid lines) and TEC gradients (d, e dashed lines) during the magnetic storms on October 29-31, 2003.

We can see that GPS positioning errors increased significantly not only within the auroral area but in the south-west of Northern America, at low enough latitudes (30-35^0 N; 240-255^0 E). High absolute values and steep TEC gradients were observed in this region concurrently (dashed line**,** Fig 2 d, e). TEC gradients can grow with additional gradient "superposition" as intensive large-scale acoustic-gravity waves (LS AGW) of auroral origin propagate (Fig 2 d). TEC variations intensity in the period range of 1-10 min increases by one order as intensive LS AGW propagates from the northeast to the southwest of the USA (Fig 2 c). Such relation for increasing of positioning errors was also assigned for magnetic storm on July 15-16, 2000 in East Siberia area (Fig.3, c, d, e). Time dependence of Dst value, the south boundary position of auroral oval and TEC gradient values are shown in Fig.3a, b and f, correspondently.

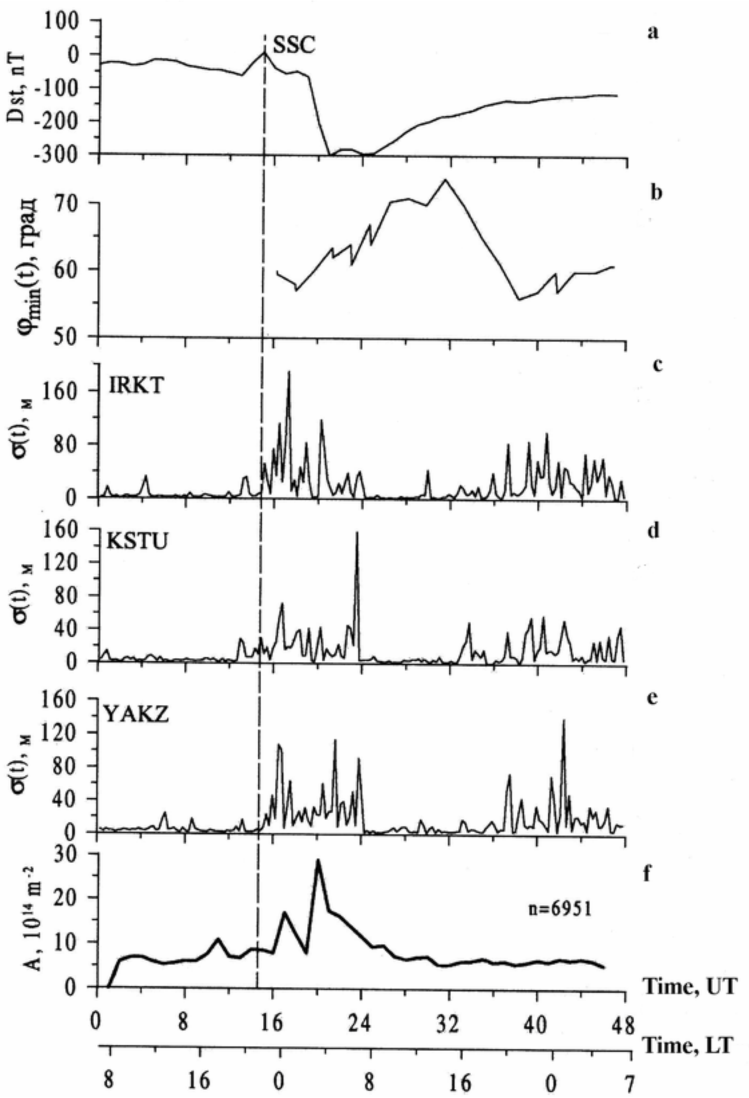

Figure 3: Dst variations (a), the south boundary position of auroral oval (b); positioning errors (c, d, e) and TEC variations intensity (f); during the magnetic storms on July 15-16, 2000 in East Siberia region.

It corresponds to enhancement of ionospheric irregularities with scales from 10 to 100 km, and in view of power character of the ionospheric irregularities' spectrum, with Fresnel zone radius size. Space-time characteristics of density distribution of phase slips of GPS signals and GPS positioning errors are close to the corresponding intensity characteristics of small-scale irregularities. Both small-scale irregularities amplitude and density of phase slips decrease with fading of LS AGW amplitude. It is in accord with the existing idea that phase slips are caused by GPS radio signals scattering on small-scale irregularities.

3.0 LATITUDIAL DEPENDENCE OF DISTRIBUTION OF GPS USER'S POSOTIONING ERRORS

Latitudinal dependence of GPS-stations positioning accuracy was obtained on a basis of analysis more then 600 GPS-stations which have well known X_0, Y_0, Z_0 coordinates. The selected stations are equipped with double –frequency GPS-receivers and comprised in the global GPS-network. These stations are set within three latitudinal regions: high-latitude (φ=50-80º N), mid-latitude (φ=20-50º N) and low-latitude

(φ<20º N). Sets of GPS-stations equipped with one of several basic receiver types such as: ASHTECH, ROGUE, AOA, TRIMBLE were selected within each of the regions. Data in a standard RINEX format [21] set on http://sopac.ucsd.edu and on FTP-server ftp://sopac/ucsd.edu/pub/ were utilized for processing and analyzing. The data set of 14 days (4 days are quiet and 10 - magnetic disturbed) in a period from 2000 to 2003 was analyzed. Considered magnetic disturbed days corresponded to six magnetic storms when Dst value was varying from -101 nT up to -358 nT. Data of 605 GPS-station for storm condition and 340 GPS-stations for quiet days were considered.

Fig. 4 plots the latitudinal dependencies of daily mean of spatial coordinate determination errors - $\Delta\overline{X}, \Delta\overline{Y}, \Delta\overline{Z}$ under quiet condition for ASHTECH, AOA, TRIMBLE and ROGUE receivers. The same dependencies are shown in Fig. 5 in the same order for magnetic storm condition. Plots in the fig. 4 were built with using data set of four quiet days (12.02.2000, 17.04.2001, 7.04.2002 and 17.04.2002). In order to create plots of latitudinal dependence in fig. 5 the data set of ten magnetic disturbed days (15-16.07.2000, 8.08.2000, 20.03.2001, 31.03.2001, 25-26.09.2001 and 29-31.10.2003) was utilized.

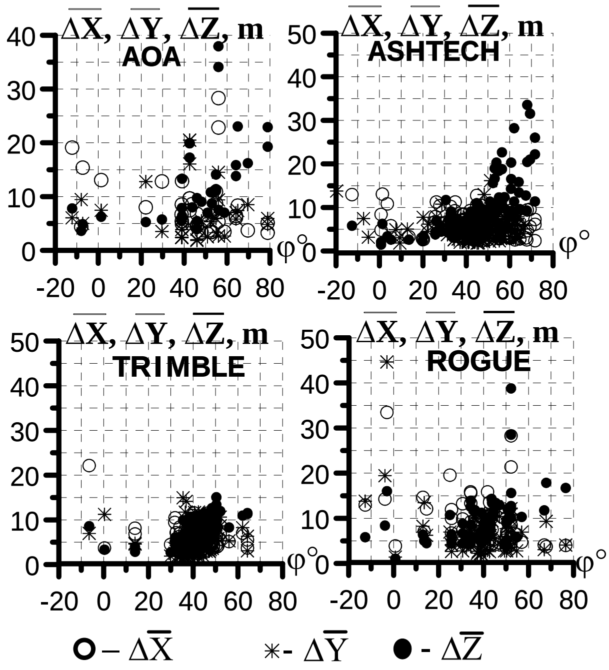

Figure 4: latitudinal dependencies of daily mean of spatial coordinate determination errors - $\Delta\overline{X}, \Delta\overline{Y}, \Delta\overline{Z}$ for ASHTECH, AOA, TRIMBLE and ROGUE receivers under quiet condition on March 25, 2003.

According to the fig 4, 5 one can conclude following.

First, absolute errors of coordinate determination are usually greater for GPS-stations at high- and low latitude comparing to these ones at mid latitudes. This dependence is more apparent under magnetic storm condition.

Second, the pointed latitudinal dependence is the most noticed for Z-coordinate determination errors: $\Delta\overline{Z}$ value increases by a factor of 1,5-2,6 at high latitudes in geomagnetically quiet condition and by a factor of 2,4-3,2 - during magnetic storms. Meanwhile $\Delta\overline{X}, \Delta\overline{Y}$ values depend on user's latitude much weaker: $\Delta\overline{X}, \Delta\overline{Y}$ - values are 20-50% higher at high and low latitudes under geomagnetic disturbances and 10-30% - in quiet condition in comparing to the mid latitudinal region in average.

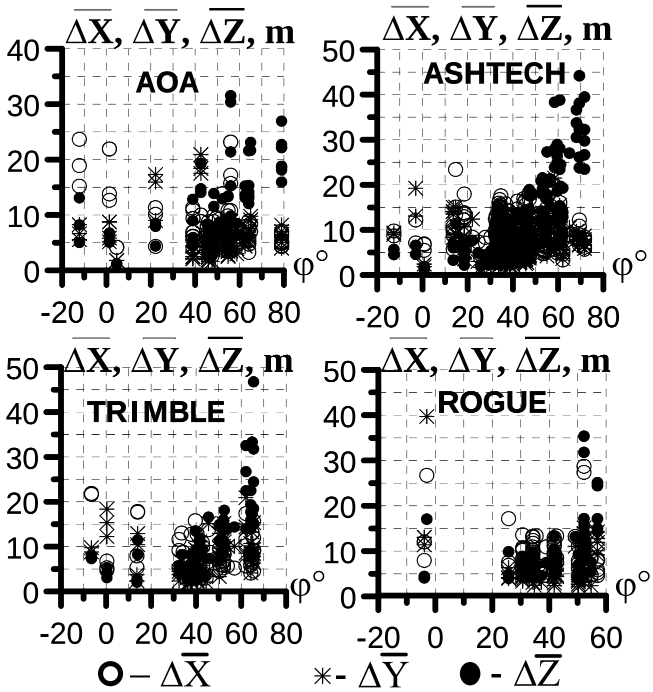

Figure 5: latitudinal dependencies of daily mean of spatial coordinate determination errors - $\Delta\overline{X}, \Delta\overline{Y}, \Delta\overline{Z}$ for ASHTECH, AOA, TRIMBLE and ROGUE receivers during magnetic storm on October 29, 2003.

Third, $\Delta\overline{Z}$ error value is grater then $\Delta\overline{X}, \Delta\overline{Y}$ ones and it depends on geomagnetic condition to the greatest extent in all cases we were considered. So $\Delta\overline{X}, \Delta\overline{Y}$ values are just slightly varying (10-30% in average) during magnetic storms and it can be both greater and less then those ones in geomagnetically quiet condition. At the same time, $\Delta\overline{Z}$ value is generally increasing during geomagnetic storms (by a factor of 1,2-2,3 in average).

4.0 POSITIONING ERRORS OF THE ORBITAL GPS USERS

In order to examine positioning errors of the orbital GPS users the low Earth orbital satellite CHAMP was chosen as an orbital object. Data set of 356 days in a period from January 1 to December 31 of 2003 from which there were 29 geomagnetically quiet and 17 geomagnetically disturbed days (including magnetic storms on October 29-31 and November 20-21 of 2003) was analyzed with the method given by [7,23]. Fig. 6 plots an example of spatial dynamics of CHAMP absolute positioning errors –Δt [m] (the full black line) and its subsatellite point location changing – φ(t), [º] (the dashed gray line) on a quiet day October 11, 2003 which was chosen as a typical quiet day. One should be noticed, that such a dynamics is typical for both quiet and disturbed condition. An analysis of the positioning error dynamics let us conclude that it comprises both systematic and random components.

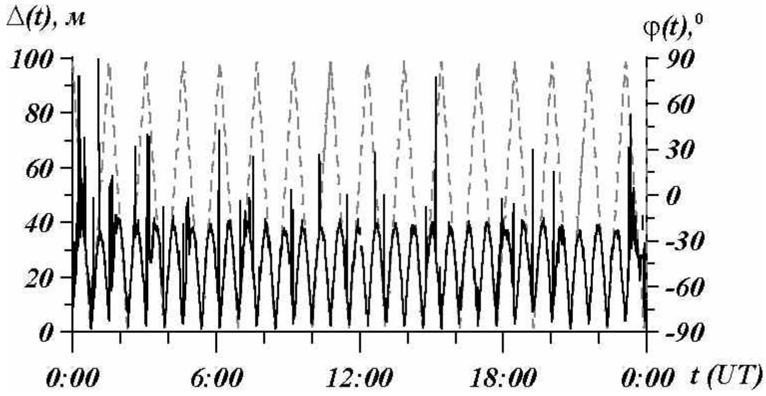

Figure 6: spatial dynamics of CHAMP absolute positioning errors –Δt [m] (the full black line) and its subsatellite point location changing – φ(t), [º] (the dashed gray line) on October 11, 2003.

Fig. 7 plots the latitudinal dependence of CHAMP coordinate determination errors. One can see that the error maximum are mostly coinciding with the crossing of a satellite path and the equatorial plane while the minima - with satellite passing over the polar zones in time. However positioning error being in such a form does not consist information about the error sign because it is only an absolute value. Thus in order to explore characteristics and determine an analytical expressions of the systematic component an investigation of the subsatellite point (φ,λ) geodetic coordinate dependence of the components of ΔX_i, ΔY_i, ΔZ_i - errors was conducted, where λ –is a longitude of the subsatellite point.

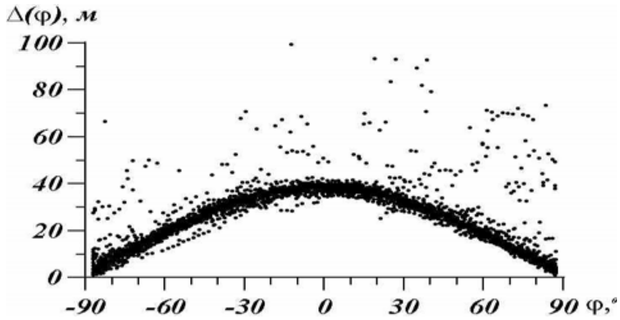

Figure 7: latitudinal dependence of CHAMP coordinate determination errors

Fig. 8 plots the diurnal subsatellite point longitudinal dependence of absolute positioning errors of X,Y-coordinate determination on October 11, 2003.

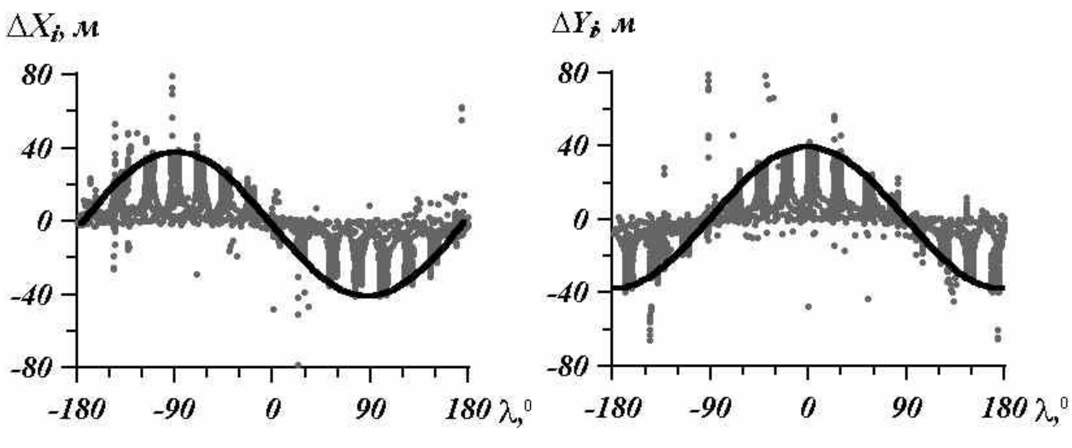

Figure 8: diurnal subsatellite point longitudinal dependence of absolute positioning errors of X,Y- coordinate determination on October 11, 2003

It was empirically found that envelopes of $\Delta X(\lambda)$ and $\Delta Y(\lambda)$- dependencies are periodic functions which can be satisfactorily fitted with the harmonic curves (black lines in the panels).

$$\Delta X_i(\lambda) = \Delta X_{\max} \sin(\lambda + \pi);$$
$$\Delta Y_i(\lambda) = \Delta Y_{\max} \cos(\lambda), \quad (1)$$

where ΔX_{max}=ΔY_{max}= 40 m – are maximal values of the systematic component of the X, Y determination errors which are found by an experimental way.

$$\Delta X_i(\varphi) = -k_X(\lambda)\varphi^2 + \Delta X_i(\lambda);$$
$$\Delta Y_i(\varphi) = -k_Y(\lambda)\varphi^2 + \Delta Y_i(\lambda). \quad (2)$$

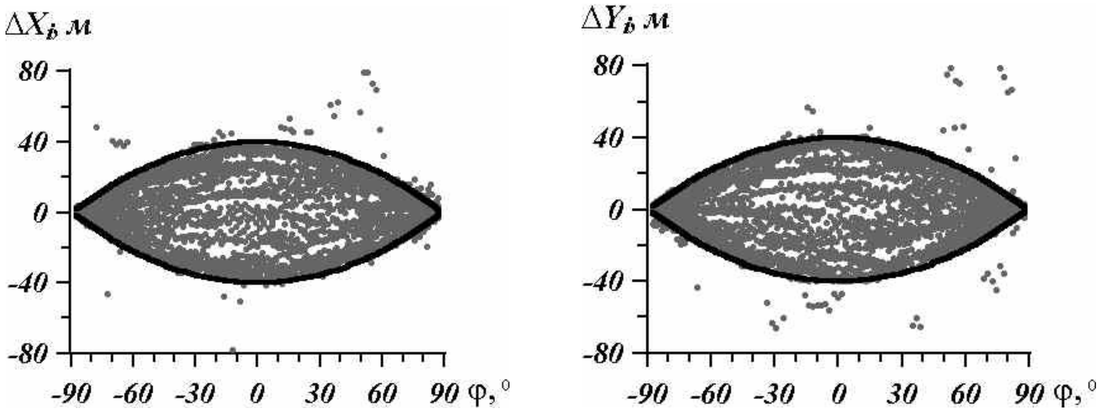

Figure 9: diurnal subsatellite point latitudinal dependence of absolute positioning errors of X,Y- coordinate determination on October 11, 2003

In its own turn the latitudinal dependencies of $\Delta X(\varphi)$ and $\Delta Y(\varphi)$ which are shown in fig. 9, can be fitted with a set of parabolic curves (black lines in the panels) having different curvature factors of its arms - $kx(\lambda)$ and $ky(\lambda)$ depending on the longitude of the subsatellite point. It was found that $kx(\lambda)$ and $ky(\lambda)$ factors are also changing according to the harmonic rule. They reach the maximum at points of maximal values $\Delta X(\lambda)$, $\Delta Y(\lambda)$ and decrease when $\Delta X(\lambda)$, $\Delta Y(\lambda)\rightarrow 0$. An expression for $kx(\lambda)$, $ky(\lambda)$ factors is given as follows

$$k_X(\lambda) = k_{X\,max}\, sin(\lambda + \pi)$$
$$k_Y(\lambda) = k_{Y\,max}\, cos(\lambda), \quad (3)$$

where $kx(\lambda)$= $ky(\lambda)$=0.005 are maximal $kx(\lambda)$, $ky(\lambda)$ values which were found empirically.

The final expression for systematic components of ΔX_i^c, ΔY_i^c is given by

$$\Delta X_i^c = -k_X \sin(\lambda + \pi)\varphi^2 + \Delta X_{\max} \sin(\lambda + \pi);$$
$$\Delta Y_i^c = -k_Y \cos(\lambda)\varphi^2 + \Delta Y_{\max} \cos(\lambda). \quad (4)$$

The subsatellite point longitudinal and latitudinal dependence of absolute positioning error ΔZ_i is shown in Fig 10.

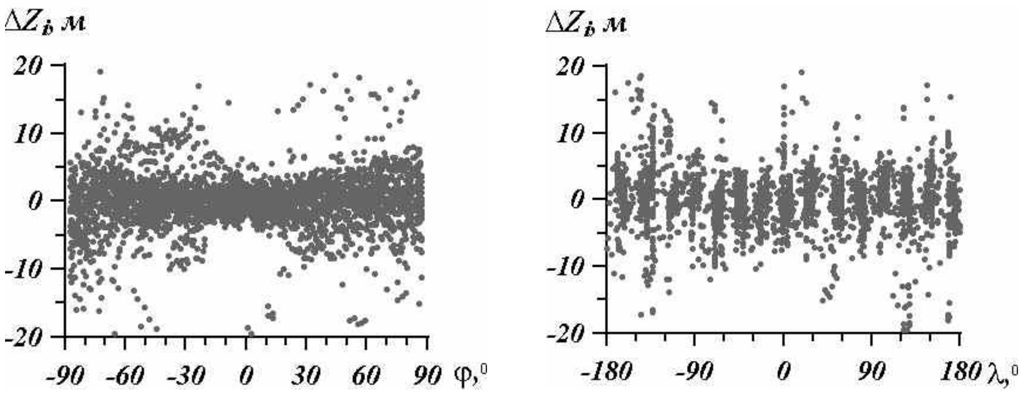

Figure 10: subsatellite point longitudinal and latitudinal dependence of absolute positioning error ΔZ_i

According to the fig.10 there is no an obvious latitudinal or longitudinal dependence of ΔZ_i error.

In order to eliminate the systematic components of positioning errors one should subtract corresponding ΔX_i^c, ΔY_i^c values (4) from the current X_i, Y_i coordinates, respectively. When the systematic component was eliminated and the second processing step was repeatedly conducted we could see that the expression (4) held true for all the processed data set. Fig. 11 plots the dynamics of CHAMP positioning errors before (panel A) and after (panel B) the systematic component was eliminated. The random component is caused by the great amount of factors, but the most significant one is the influence of the radio propagation media.

In order to estimate to what extent the near Earth space environment affects orbital user's positioning accuracy we analyzed the data set, which was collected under different geophysical conditions in the period from January 1 to December 31, 2003.

Three days when the Kp-index didn't exceed 2 at every 3-hour interval were chosen as magnetically quiet and five days when Kp-index was equal or higher than 8 were considered as magnetically disturbed ones.

Fig. 12 shows the probability distribution of CAHMP positioning errors, which range in value from 0 to 80 meters under magnetically quiet (black cross-hatched bars) and magnetically disturbed condition (gray bars). According to the fig 12 one can conclude that the most probable value of the positioning error didn't exceed 10 meters after the systematic component was eliminated. Thus, GPS can be used for orbital objects positioning as the navigational supply requirements for the objects of such a class are satisfied [5]. However, a probability of the occurrence of the error, which exceeds 30 m during magnetic storms, is half as high as at magnetically quiet condition.

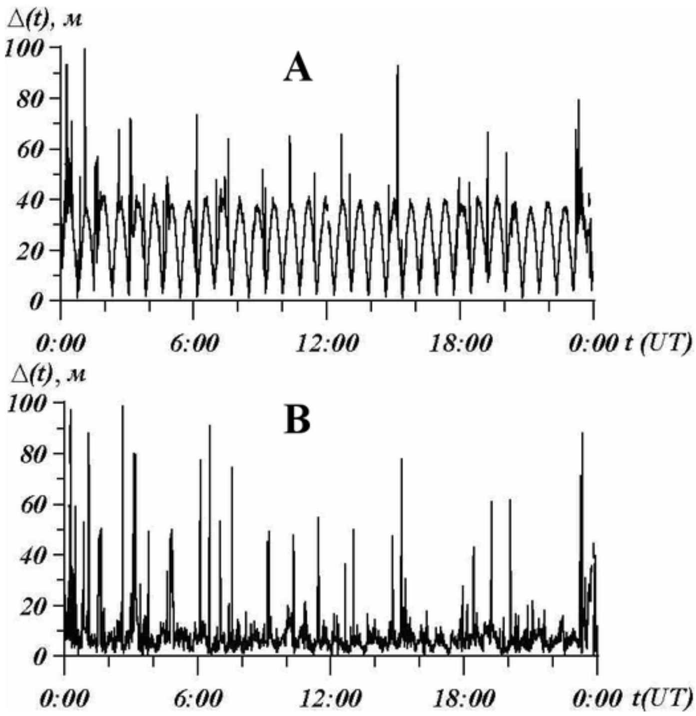

Figure 11: dynamics of CHAMP positioning errors before (panel A) and after (panel B) the systematic component was eliminated

In order to form an estimate near Earth space environment influence on orbital user's positioning continuity an assessment of CHAMP positioning slips duration (Δt_{sb}) and position slips number ($N_{1,2}$) in double frequency mode at every 0,5-hour motion interval were considered under different geomagnetic conditions in the period from January 1 to December 31, 2003. 29 days were chosen as geomagnetically quiet when Kp-index at every 3-hour interval didn't exceed 2 and 17 days when Kp-index was equal or higher then 7 were considered as geomagnetically disturbed ones.

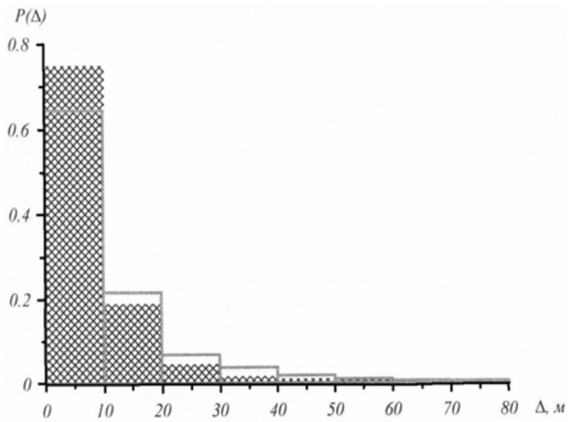

Figure 12: Probability distribution of CAHMP positioning errors under magnetically quiet (black cross-hatched bars) and magnetically disturbed condition (gray bars)

Fig. 13 plots the Probability distribution of distribution of slip duration for geomagnetically quiet and geomagnetically disturbed conditions (black bars and gray bars, respectively). As above mentioned we defined the positioning slip, as an event when positioning accuracy didn't satisfy a condition (5). Taking in account that the time interval of data read-out in a source RINEX-file is 10 sec, slip duration is given by

$$\Delta t_{сб} = N_{1,2} \cdot 10\,c. \tag{5}$$

According to the fig.13 one can see that the slip duration can reach as much as 90 sec under geomagnetically disturbed condition. Upon this the probability of slips occurrence which have 50 sec duration or longer during magnetic storms is ~ 5 times as high as at magnetically quiet condition. Under magnetic disturbances the probability of single 10 sec duration positioning failures occurrence increases by 1,4 times as well. The cause of this phenomenon is that intensity of small-scale electron density irregularities increases and satellite signal scattering from the irregularities increases too under geomagnetically disturbed conditions. As a result, the level of the nautical signal can be falling down comparing to the noise level at the reception point.

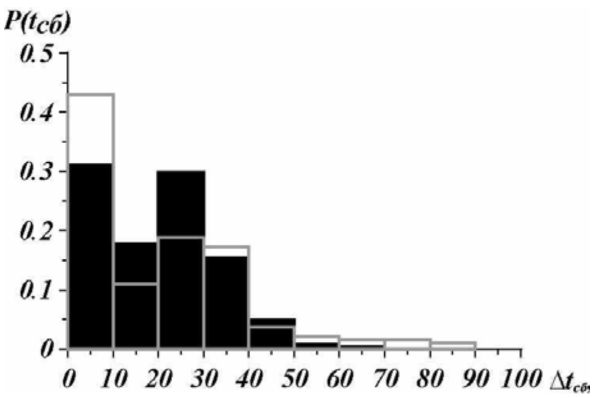

Figure 13: Probability distribution of distribution of slip duration for geomagnetically quiet and geomagnetically disturbed conditions (black bars and gray bars, respectively)

Fig. 14 plots a time dependence of CHAMP positioning failures number at every half an hour interval on a magnetically quiet day October 11, 2003 (in the panel A) and on a strong stormy day October 29, 2003 (in the panel B).

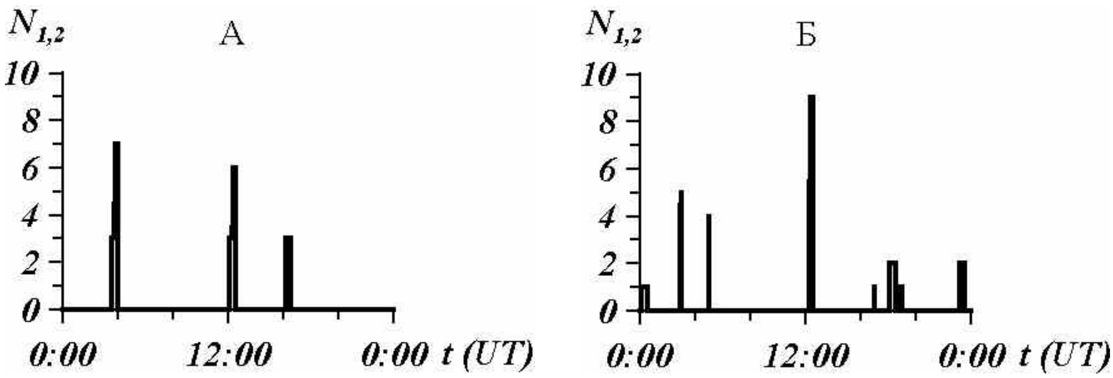

Figure 14: time dependence of CHAMP positioning failures number at every half an hour interval on a magnetically quiet day October 11, 2003 (in the panel A) and on a strong stormy day October 29, 2003 (in the panel B)

In the fig.14 on can see that positioning failures number at every half an hour interval of CHAMP motion increased and reached as much as 9 during the magnetic storm. Both the total diurnal number of the slips and the number of failures, which had 10-20 sec duration increased as well. It proves that intensity of small-scale electron density irregularities, satellite signal are scattered from, increases during magnetic storms.

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